IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Applicant:	Nemmara Chithambaram et al.	Examiner:	Temica M. Beamer
Serial No.:	10/037,805	Group Art Unit:	2681
Filed:	December 26, 2001	Docket:	G&C 30566.201-US-01
Title:	MOBILE DEVICE LOCATOR ADAPTER SYSTEM FOR LOCATION BASED SERVICES		

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By: Jason S. Feldmar
Name: Jason S. Feldmar

CITATION OF PRIOR ART IN PATENT FILE (37 C.F.R. §1.501(a))

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U.S. Patent No.: 6,249,252 Issued: June 19, 2001 To: Dupray

UK Patent Application No.: GB 2352134 Published: January 17, 2001
Applicant: Aircom International Limited Inventors: Stephen Mockford et al.

A copy of each document is provided herewith. The references were cited in a European Search Report dated August 25, 2005, pursuant to a related European patent application, and are submitted for informational purposes only.

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Please direct any response or inquiry to the below-signed attorney at (310) 641-8797.

Respectfully submitted,

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Date: August 30, 2005

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Notice of Allow. Date: March 23, 2005
Confirmation No.: 6253

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(54) Abstract Title
Locating mobile telephones

(57) A method of locating a mobile telephone handset comprises the steps of (i) calculating a predicted signal property such as signal strength or observed time difference for a plurality of possible locations for the handset, (ii) comparing the predicted signal property with a measured signal property and (iii) deriving from the comparison a probability that the handset is at one or more of the locations. The method can be refined by combining the thus derived probability map with a probability map based on geographical information or historical data or both. Thus a peak probability which moves along a path parallel to a road indicates the handset is on that road. Several probability maps for example based on time differences, signal strength, geographical data and historical data can be combined simultaneously or sequentially to identify a peak probability.

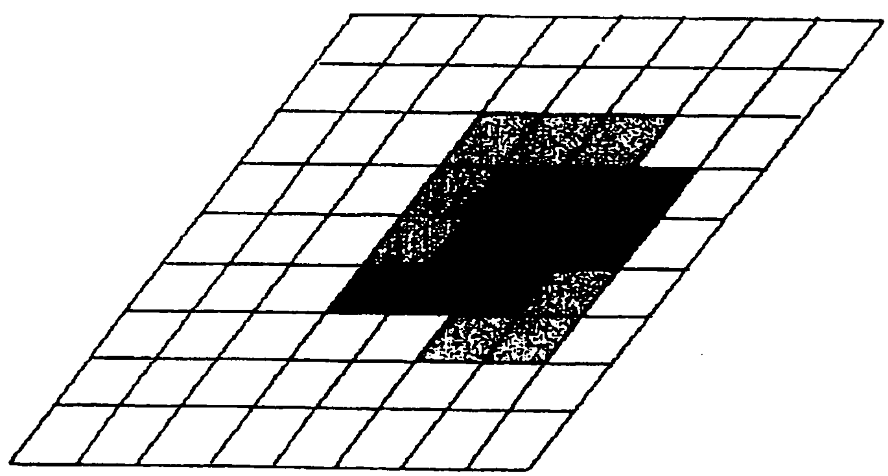

Fig 3

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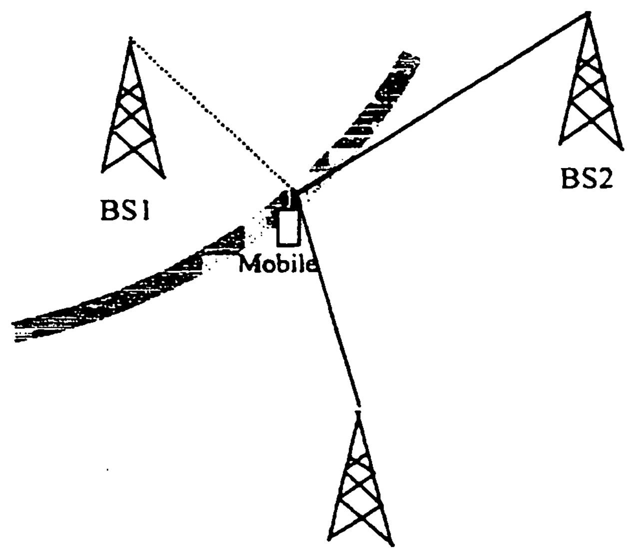


Fig 1

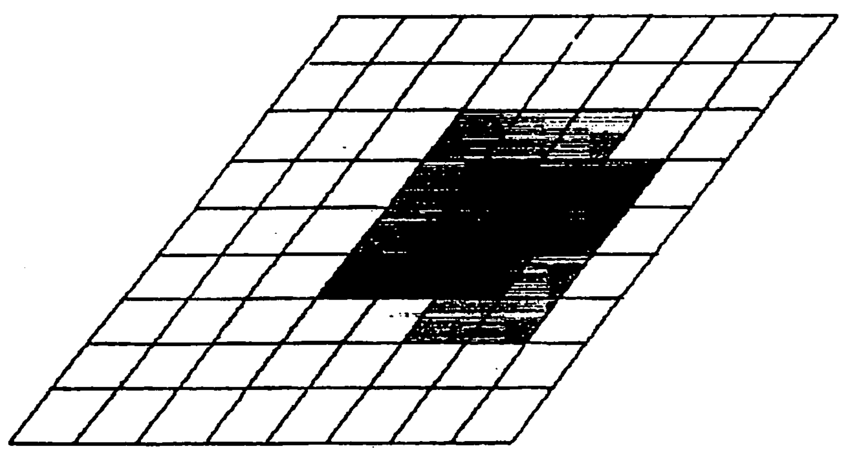


Fig 3

Fig 2a

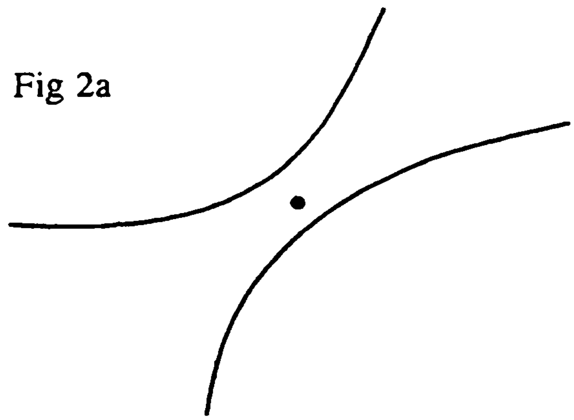


Fig 2b

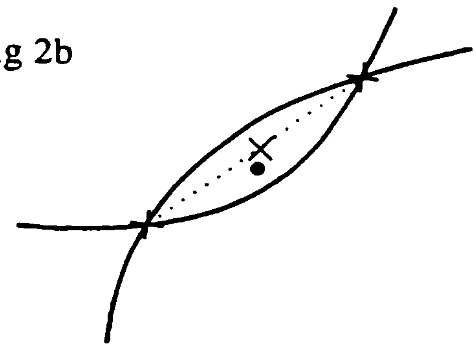


Fig 2c

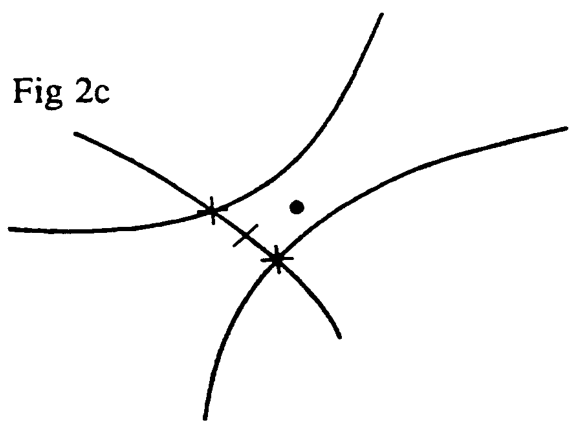


Fig 2d

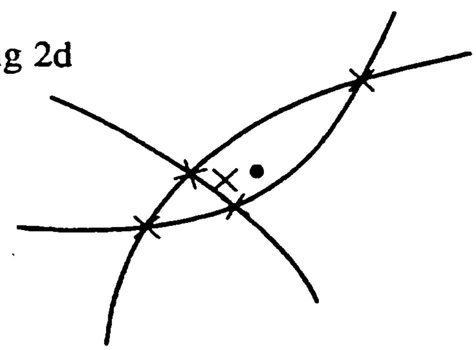
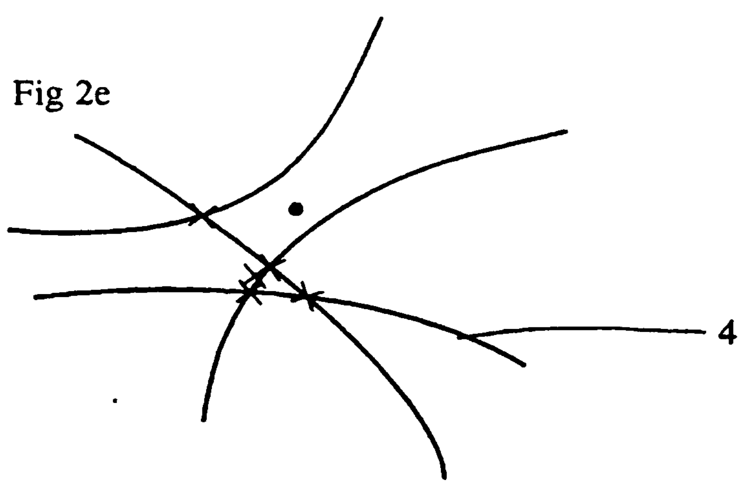


Fig 2e



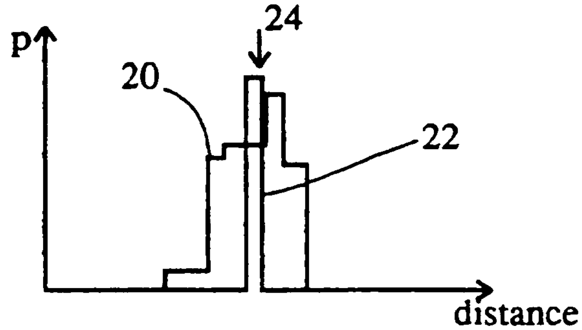

p
24
20
22
distance

Fig 4

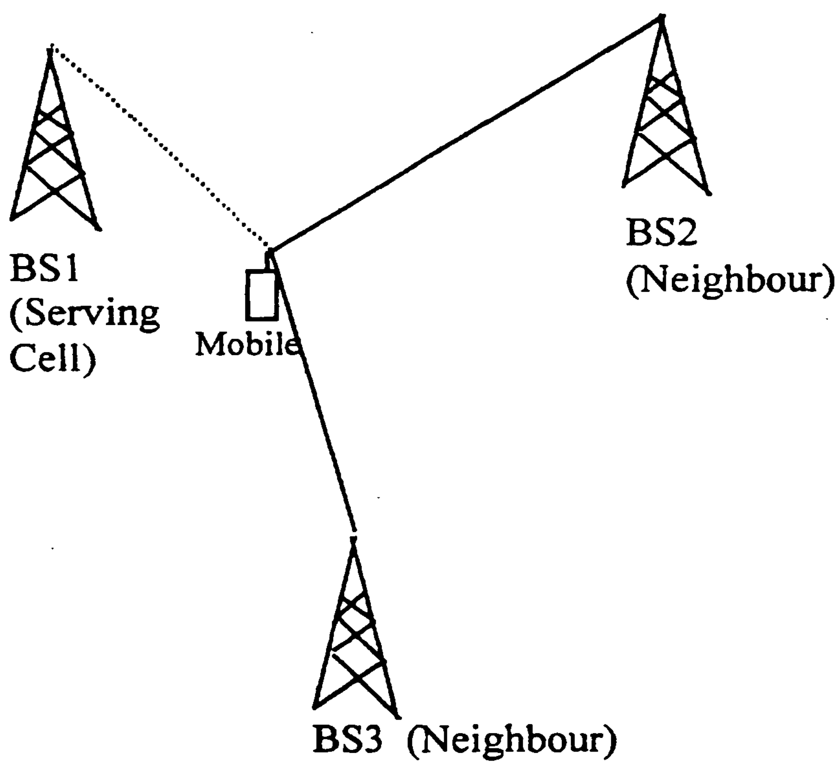
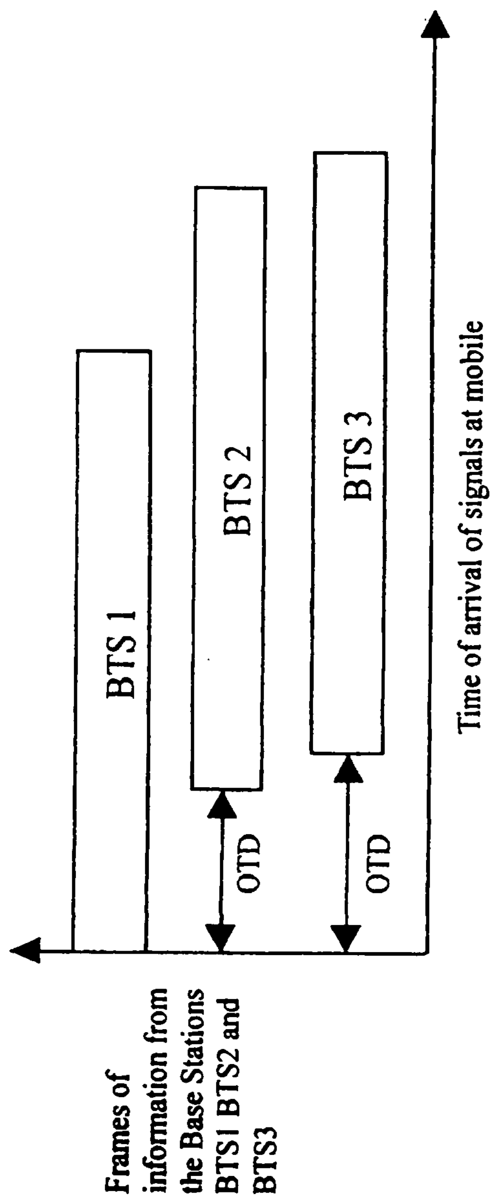

BS1
(Serving
Cell)
Mobile
BS2
(Neighbour)
BS3 (Neighbour)

Fig 5



BTS 1
BTS 2
BTS 3
OTD
OTD
Time of arrival of signals at mobile
Frames of information from the Base Stations BTS1 BTS2 and BTS3

LOCATING MOBILE TELEPHONES

The present application relates to the location of mobile telephone handsets.

A number of services could benefit from the availability of accurate location information relating to mobile telephones. These include home zone billing, fleet management, emergency road services, navigation, public transport management, network engineering and optimisation and traffic information.

At present, it is only possible to locate a particular handset by identifying the base station which is serving that handset. This will normally be the closest base station. In a rural area, this could cover a large geographical area.

Existing US FCC's E911 requirements will, in time, require a handset to be locatable to an accuracy of 125m for 67% of calls and within 300m for 95% of calls to permit the speedy arrival of emergency services and/or breakdown services.

Trials have shown that although accurate location can be achieved by the use of observed time differences, the method requires complex hardware to be added to the network. The method relies on the fact that GSM telephones are served by

a single base station, and measure signals from up to six neighbouring cells. It also relies on additional hardware to perform timing measurements of all cells in a network. The signals measured at the mobile from the server and neighbours will arrive at different times depending on distance. The absolute time of transmission is not known, but the time difference observed between two base stations together with timing measurements made on the network allow a hyperbola to be constructed linking points of equal time difference. With two such hyperbolae derived from three base stations, the intersection can be calculated to yield the location of the handset. Figure 1 shows this schematically.

This approach is difficult to deploy in practice since it requires hardware changes to both the network and the mobiles. The changes required to the network involve one of two options. Either the deployment of a network of Location Measurement Units (LMUs) which measure the transmission time of cells or accurate synchronisation of the transmission times for all cells in the network. The latter is an unlikely choise, as it would involve costly upgrades of all base stations. The changes required to the mobile involve more accurate measurement of Observed Time Differences from surrounding cells. Furthermore, the mathematics for calculating the intersection is not trivial and the time differences will have an associated error, illustrated in Figure 2, so the hyperbolae may not intersect at all (Figure 2a), or may intersect at several locations (Figures 2b). As more time differences are employed, which might be thought to improve accuracy, the mathematics becomes still more complex as it is unlikely that the hyperbolae will intersect at a common location (Figures 2c, 2d). Figure 2e shows this situation most clearly, in which the addition of hyperbola 4 has in fact worsened the estimated location.

The present invention provides a method of locating a mobile telephone handset using the properties of the transmitted signal, such as the observed time differences or the received signal strength, to calculate a probability map for the location of the handset. This side-steps the complex mathematics involved in

finding the intersections of hyperbolae. Use of the received signal strength has the further advantage that no hardware modifications are required to the network and no modifications at all are required to the mobile handset. Given this, the method is particularly useful in locating legacy mobiles in any situation where a positioning method is being deployed in a network.

The present invention therefore provides a method of locating a mobile telephone handset comprising the steps of (i) calculating a predicted signal property for a plurality of possible locations for the handset, (ii) comparing the predicted signal property with the measured signal property and (iii) deriving from the comparison a probability that the handset is at one or more of the said locations.

The possible location can, for example, be distributed on a grid located at a likely area for the handset. That likely area can be the coverage area of the serving base station, or it could be an area designated as high probability by an earlier iteration of the same method.

This method is highly advantageous over seeking intersections of hyperbolae since the computation required is simple and well suited to automation. Thus, it can be processed swiftly. Furthermore, it is immune to errors in the measured signal since only a probability is calculated as opposed to a precise location.

Furthermore, this method can be refined significantly by combining the thus derived probability map with an *a priori* probability map, for example based on geographical information. This relies on the fact that it is intrinsically more likely that a handset will be located (e.g.) on a road or in a built-up area, as opposed to the middle of a desert. The combination of the two probability maps can be a simple cross product of the 2D vectors, illustrated by way of example (in one dimension) in Figure 4. Line 20 is the varying probability derived from the method set out above, whereas line 22 is a step function inferred from local geographical

data, in this case a road passing through a barren area. Thus, the most likely position of the handset is at 24.

An alternative a priori probability map is one based on historical data, possibly combined with geographical data. Thus, a peak probability which moves along a path parallel to a road indicates that the handset is on that road. This is particularly so if the peak probability is moving at speed. A bend in the road would also give information as to the location along the road. Alternatively, a long rest period adjacent a spot feature such as a congested junction offers a refinement to an instantaneous position. Previous position data also enables a corrective displacement relative to the peak probability to be calculated.

The preferred signal properties are time differences and signal strength, particularly signal strength for the reasons given above. Where signal strength is employed, it is also preferred that pre-calculated signal strength arrays are loaded for the serving cell and any measured cells involved.

Several probability maps could be combined simultaneously or sequentially. For example, the maps based on time differences, geographical data, historical data and signal strength could all be crossed to identify a peak probability.

An embodiment of the present invention will now be described by way of example, with reference to the accompanying drawings, in which:-

Figure 1 is a schematic illustration of the intersecting hyperbolae method;

Figure 2 is a schematic illustration of errors in the intersecting hyperbolae method;

Figure 3 illustrates an example of a probability map;

Figure 4 shows the combination of probability maps;

Figure 5 shows a part of a GSM network; and

Figure 6 illustrates time differences in signal arrival times.

Background to GSM networks

In a GSM network mobiles are only served by one base station but they always measure signals from neighbouring cells (typically six neighbours) (see Figure 5). This signals from these base stations all arrive at different times depending on when they were transmitted and how far away they are from the mobile. This document will conform to the following naming convention for these quantities. They are:

OTD: Observed Time Difference. This is the time difference between the arrival of the signal at the mobile from the serving base station and the arrival of the signal from a neighbouring base station. This is illustrated in Figure 6.

RTD: Real Time Difference. This is the difference between the transmission of a frame from one base station (BS) and the transmission of a frame from another. If BS1 transmits a frame at time $t=5$ and BS2 transmits a frame at time $t=7$ then the RTD between them is $7-5=2$. If all the base stations in a network transmit their frames at the same time then the network is said to be synchronised and all the RTDs are zero.

GDT: Geometric Time Difference. This is the part of the time difference of the arrival of two frames due to geometric separation of the sites and the mobile. This difference in time taken for a transmission to travel from BS1 to the mobile and the time taken for a transmission to travel from BS2 to the mobile.

The OTD for any pair of sites is the sum of the RTD and the GTD (OTD = RTD + GTD).

The mobile measures the OTD for the serving base station and each of the neighbours. The GTD is what is required to calculate the position of the mobile. This can either be obtained by subtracting the RTD from the OTD or by using a synchronised network such that the OTD and the RTD are the same. In this description, it is assumed that the network is synchronised, but the correction is straightforward. It is also assumed that propagation from the base stations is line of sight. This assumption allows us to convert the time difference to a distance difference by dividing by the speed of light.

<u>Location method</u>

As set out above, location of mobile handsets according to preferred embodiments of the present invention can be by use of observed time differences or signal strength measurements. In this example, the detailed explanation of the method will be given mainly in relation to observed time differences. However, the principal as applied to measured signal strengths is identical and the resulting mathematics equally applicable.

Instead of constructing a hyperbola for each OTD measurement, a preliminary estimate of the location of the mobile is made (e.g. using the cell of origin) and then a grid is constructed around the estimated position. Then for each square of the grid, a prediction is made of what the OTD or signal strength measurements would be, for all the measured base stations, if the mobile were in that square. In practice, the signal strength for relevant areas around each site would be pre-calculated so that the process would involve loading precalculated arrays of predicted signal strength instead of a more time-consuming signal strength calculation.

Those predictions are compared with the measured values to give a figure of probability of the mobile being in that square. A graphical representation of a probability map is shown in Figure 3. The darker the shading, the higher the probability of the mobile being in that square. The resolution of the grid could either by very fine - say 1m or 5m, or to reduce the calculations required, the process could be done in stages with an initial coarse grid (say 100m) followed by smaller and finer grids centred on the high probability area.

Further advantages can be added by combining the information from the probability map with information about the area concerned. This might include high-resolution digital mapping data information or corrections for areas where propagation is known to be non-line-of-sight. Alternatively, the a priori map could simply be an averaged historical map of handset location.

Since some of the calculations involved in calculated the predicted OTDs, which are compared with the real measurements, do not change over time, it may be possible to speed up the location calculation by doing a certain amount of calculation in advance and storing it for later use.

The remainder of this description outlines the numerical method for computing the location of a handset based on the measured delay between signals received from several sites. The only restriction on the method is that the measured delays are statistically independent. A simple example is the situation where all delays are relative to the signal received from one principal site. The method is also applicable to the use of received signal strength measurements (rxLev) made on the handset. These measurements are assumed to be available through an interface to the BSC (Base Station Controller). The method would be the same if a mobile were providing the information via a short message.

In order to obtain an estimate for the handset location, one must also make assumptions regarding the errors in the measured delays or signal strengths. The

following assumes that these errors are normally distributed, but further experimentation may show that an alternative distribution should be adopted.

In the following;

lower case letters are used to signify continuous random variables, e.g. x;

a lower case p() signifies a probability density function, e.g. p(x);

upper case letters are used to denote a tiny range of values of a continuous random variable, e.g.

X refers to values of x lying in the range $[X-\delta X, X+\delta X]$

Y refers to values of y lying in the range $[Y-\delta Y, Y+\delta Y]$;

an upper case P() signifies a probability. This is invariably obtained by integrating a probability density function between appropriate limits:

$$P(X) = \int_{X-\delta X}^{X+\delta X} p(x)dx$$

We shall write integrals of the above form using the more concise notation

$$P(X) = \int_{X} p(x)dx$$

For simplicity of presentation it will be assumed that there are just two independent time difference (OTD) measurements (T_1, T_2) or corresponding signal strength measurements. The generalisation to higher numbers of independent measurements is trivial. Note that the measurements have been written in upper case. This signifies that they refer to finite ranges $[T_1-\delta T_1, T_1+\delta T_1]$ and $[T_2-\delta T_2, T_2+\delta T_2]$ of continuous random variables t_1 and t_2. The widths ($2\delta T_1$ and $2\delta T_2$) of these ranges are determined by the accuracy of the measuring equipment.

It is necessary to calculate:

$$P(X, Y \mid T_1, T_2) \quad (1)$$

This is the probability that the handset is at (X,Y) given that we have timing measurements (T_1,T_2) or corresponding signal strength measurements.

We can use Bayes' Theorem (i.e. that P(A,B) = P(A|B) = P(B|A)P(A) to write (1) as

$$P(X,Y \mid T_1,T_2) = \frac{P(X,Y,T_1,T_2)}{P(T_1,T_2)} \tag{2}$$

The terms on the right-hand side can be written as integrals of the joint probability density functions p(x,y,t_1,t_2).

$$P(X,Y \mid T_1,T_2) = \frac{\int_{T_1}\int_{T_2}\int_{X}\int_{Y} p(x,y,t_1,t_2)\,dx\,dy\,dt_1\,dt_2}{\int_{T_1}\int_{T_2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(x,y,t_1,t_2)\,dx\,dy\,dt_1\,dt_2} \tag{3}$$

We can use Bayes' Theorem again to write P(x,y,t_1,t_2) in terms of things that can be calculated:

$$P(X,Y \mid T_1,T_2) = \frac{\int_{T_1}\int_{T_2}\int_{X}\int_{Y} p(t_1,t_2 \mid x,y)\,p(x,y)\,dx\,dy\,dt_1\,dt_2}{\int_{T_1}\int_{T_2}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(t_1,t_2 \mid x,y)\,p(x,y)\,dx\,dy\,dt_1\,dt_2} \tag{4}$$

The factor p(x,y) is simply the probability density function for a spatial location. The simplest assumption that could be made is that p(x,y) is uniformly distributed over the area we are considering. Other choices are possible and may give improved results. for example, areas of high traffic could be given a higher value than areas of low traffic.

Assuming that p(x,y) is uniformly distributed over the mobile's serving cell, (4) can be simplified by cancelling the p(x,y) terms, and replacing the spatial integral in the denominator by an integral over the serving cell.

$$P(X,Y \mid T_1,T_2) = \frac{\int_{T_1}\int_{T_2}\int_X\int_Y p(t_1,t_2 \mid x,y)\,dx\,dy\,dt_1\,dt_2}{\int_{T_1}\int_{T_2}\oint\!\!\oint_{\substack{Serving\\Cell}} p(t_1,t_2 \mid x,y)\,dx\,dy\,dt_1\,dt_2} \tag{5}$$

The factor $p(t_1,t_2|x,y)$ is the probability density function for the timing measurements (or corresponding signal strength measurements) given that the handset is at (x,y). This can be calculated if some assumptions are made about the errors in the timing or signal strength measurements. The locations of the transmitting sites are known, and for any mobile location (x,y) the ideal time measurements (or corresponding signal strength measurements) can be calculated that would arise in the absence of error. These can be called "ideal measurements" $t_1^\bullet(x,y)$ and $t_2^\bullet(x,y)$. Assuming also that the errors in the measured times are normally distributed with zero mean (but possibly different variances σ_1 and σ_2).

Since the measurements are statistically independent, we can write

$$p(t_1,t_2 \mid x,y) = \frac{1}{\sqrt{2\pi}\sigma_1}\exp\left(-\frac{(t_1-t_1^\bullet)^2}{2\sigma_1^2}\right)\frac{1}{\sqrt{2\pi}\sigma_2}\exp\left(-\frac{(t_2-t_2^\bullet)^2}{2\sigma_2^2}\right) \tag{6}$$

Now if our timing or strength measurements are made with sufficiently high accuracy ($\delta t_1 << \sigma_1$, $\delta t_2 << \sigma_2$) the integrals dt_1dt_2 can be approximated in (5) to give

$$P(X,Y \mid T_1,T_2) \approx \frac{\int_X\int_Y \frac{1}{\sqrt{2\pi}\sigma_1}\exp\left(-\frac{(T_1-t_1^\bullet)^2}{2\sigma_1^2}\right)\frac{1}{\sqrt{2\pi}\sigma_2}\exp\left(-\frac{(T_2-t_2^\bullet)^2}{2\sigma_2^2}\right)dx\,dy}{\oint\!\!\oint_{\substack{Serving\\Cell}} \frac{1}{\sqrt{2\pi}\sigma_1}\exp\left(-\frac{(T_1-t_1^\bullet)^2}{2\sigma_1^2}\right)\frac{1}{\sqrt{2\pi}\sigma_2}\exp\left(-\frac{(T_2-t_2^\bullet)^2}{2\sigma_2^2}\right)dx\,dy} \tag{7}$$

At a small enough spatial resolution, the remaining integrals in (7) can be approximated in a similar manner. This is essentially what the following algorithm does.

Algorithm for determining handset position

a) Scan through an area with fixed step sizes in the x and y directions. These should be sufficiently small.

(b) At each pixel (X,Y), calculate the "ideal measurements" $t_1^*(X,Y)$ and $t_2^*(X,Y)$, and then evaluate

$$V(X,Y) \equiv \frac{1}{\sqrt{2\pi}\sigma_1}\exp\left(-\frac{(T_1 - t_1^*)^2}{2\sigma_1^2}\right)\frac{1}{\sqrt{2\pi}\sigma_2}\exp\left(-\frac{(T_2 - t_2^*)^2}{2\sigma_2^2}\right) \tag{8}$$

(c) The probability that the handset is in a pixel (X,Y) is simply

$$P(X,Y \mid T_1,T_2) \approx \frac{V(X,Y)}{\sum_{\substack{\text{Pixels in} \\ \text{Serving Cell}}} V(X,Y)} \tag{9}$$

Note that (9) is an approximation to (7) but is valid if the pixels are sufficiently small. Clearly, the smaller the pixel size, the better the approximation.

(d) Once $P(X,Y|T_1T_2)$ has been worked out at every pixel in the search area, the most likely location for the handset is given by the expectation

$$E\begin{pmatrix} X \\ Y \end{pmatrix} = \sum_{\substack{\text{Pixels In} \\ \text{Serving Cell}}} P(X,Y \mid T_1,T_2)\begin{pmatrix} X \\ Y \end{pmatrix} \tag{10}$$

e) The variance (if calculated) will give an idea of the accuracy for the prediction (i.e. how well localised it is).

$$\sigma^2 = \sum_{\substack{\text{Pixels In} \\ \text{Serving Cell}}} P(X,Y \mid T_1,T_2)\begin{pmatrix} X - E(X) \\ Y - E(Y) \end{pmatrix} \bullet \begin{pmatrix} X - E(X) \\ Y - E(Y) \end{pmatrix} \tag{11}$$

This could be used to draw a bounding circle around the point $E\begin{pmatrix} X \\ Y \end{pmatrix}$.

Alternatively, if all calculations are stopped at step (b) and the largest V(X,Y) in the search area issued as an indication of the handset position, then the same result could be obtained by simply taking the minimum of

$$\chi^2 = \left(\frac{T_1 - t_1^\bullet}{\sigma_1}\right)^2 + \left(\frac{T_2 - t_2^\bullet}{\sigma_2}\right)^2$$

i.e. use X^2 as a maximum likelihood estimator for (X,Y).

On an implementation level it is assumed that the relevant pre-calculated signal strength arrays could be downloaded to the BSC or other mobile location platform on a regular basis.

The present invention therefore offers a numerical method for calculating the location of a handset based on independent timing or signal strength measurements. The method attempts to determine the most likely position for a handset and is able to give an idea of the accuracy of the result. The method has been described above in a general form and the final implementation would allow the user to "tune" the method by varying the following parameters:

- Pixel size. This needs to be sufficiently small.
- Distribution functions for the time delays between pairs of sites or signal strengths from different cells. It is possible to experiment with different standard deviations.
- p(x,y). This acts as a weighting function when calculating the V values. For example, the calculation could be biased to favour areas of high traffic.

The method proposed herein is computationally expensive compared to other techniques of handset positioning (based on intersecting hyperbolae for example), but is correspondingly more straightforward to automate. It also makes use of only one set of timing measurements (or corresponding signal strength measurements) and so it does not benefit from previous measurements/calculations that may be available to the system. Prior knowledge of this sort can be used to obtain faster (and more reliable) estimates of handset position.

It will of course be apparent to the skilled reader that many variations could be made to this embodiment without departing from the scope of the present invention.

CLAIMS

1. A method of locating a mobile telephone handset comprising the steps of;
   (i) calculating a predicted signal property for a plurality of possible locations for the handset,
   (ii) comparing the predicted signal property with the measured signal property and
   (iii) deriving from the comparison a probability that the handset is at one or more of the said locations.

2. A method according to claim 1 in which the thus derived probability map is combined with an a priori probability map.

3. A method according to claim 2 in which the a priori probability map includes geographical information.

4. A method according to claim 2 or claim 3 in which the a priori probability map includes historical data.

5. A method according to any one of claims 2 to 4 in which the combination of the two probability maps is a product of the two probabilities at each location.

6. A method according to any one of claims 2 to 4 in which there are several probability maps each based on a different factor.

7. A method according to claim 6 in which the maps are combined sequentially.

8. A method according to claim 6 in which the maps are combined simultaneously.

9. A method according to any preceding claim in which the signal property is the measured signal strength.

10. A method according to any one of claims 1 to 8 in which the signal property is an observed time difference.

11. A method according to any one of claims 1 to 8 in which a probability map is also generated based upon observed time differences.

12. A method of locating mobile telephones substantially as described herein with reference to and/or as illustrated in the accompanying drawings.

13. Apparatus for locating mobile telephones adapted to implement a method as set out in any one of the preceding claims.

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Application No: GB 0011660.8 **Examiner:** Gareth Griffiths
Claims searched: All **Date of search:** 7 November 2000

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.R): H4L (LDRRS, LDSL)

Int Cl (Ed.7): H04Q 7/38

Other: Online Databases: WPI, EPODOC, JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
X, P	GB2333664 A	(MULTIPLE ACCESS COMMUNICATIONS) p.4 lines 5-20	1, 9
X	GB2291300 A	(MOTOROLA) p.3 lines 6-26	1-11
X, P	EP0982964 A2	(LUCENT) p.2 line 53 - p.3 line 5	1, 9, 10
X, P	WO00/18148 A1	(PPM) p.5 lines 4-15	1, 9, 10
X	WO99/18747 A1	(NOKIA) p.4 lines 5 - 22	1-11
X	WO98/15149 A1	(NOKIA) p.4 line 5 - p.5 line 14	1-11

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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